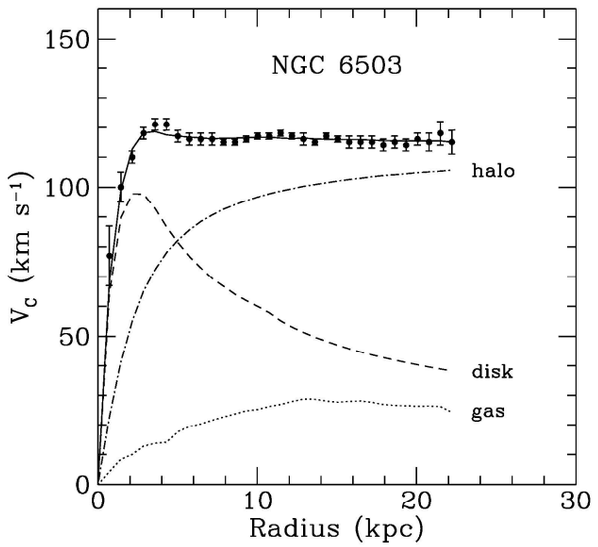
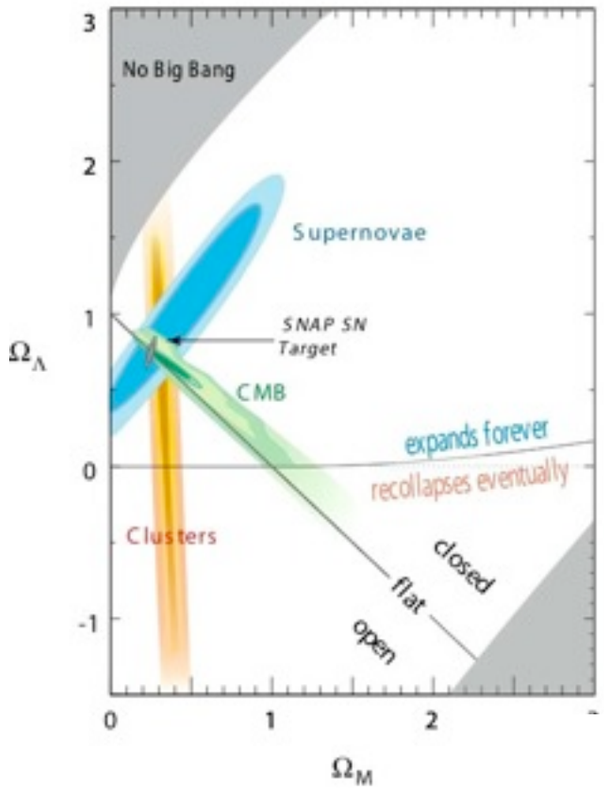
WIMP Dark matter at Colliders

Lian-Tao Wang
University of Chicago

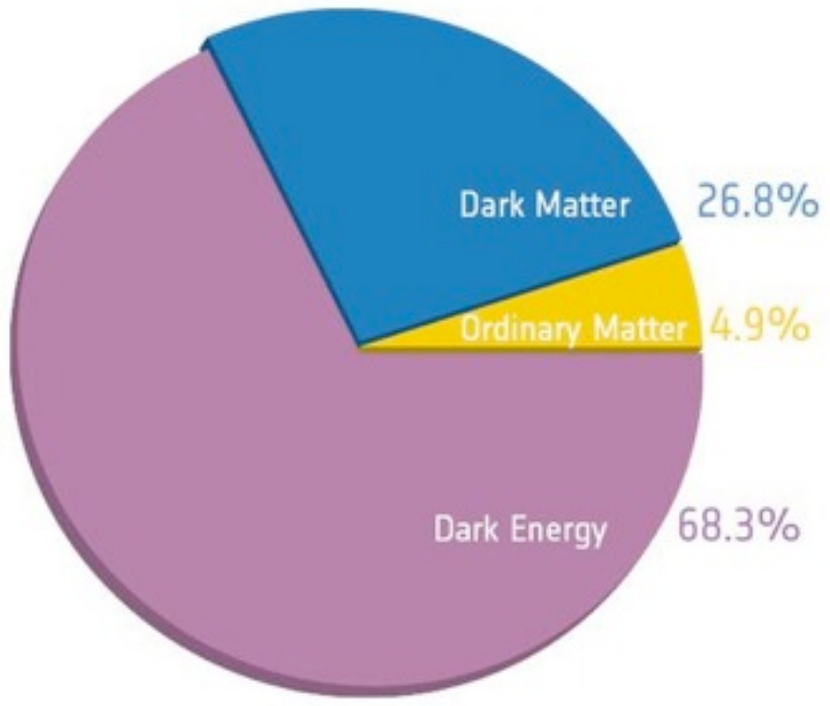
Next steps in the energy frontier, FNAL, Aug. 27, 2014

We have solid evidence for dark matter:





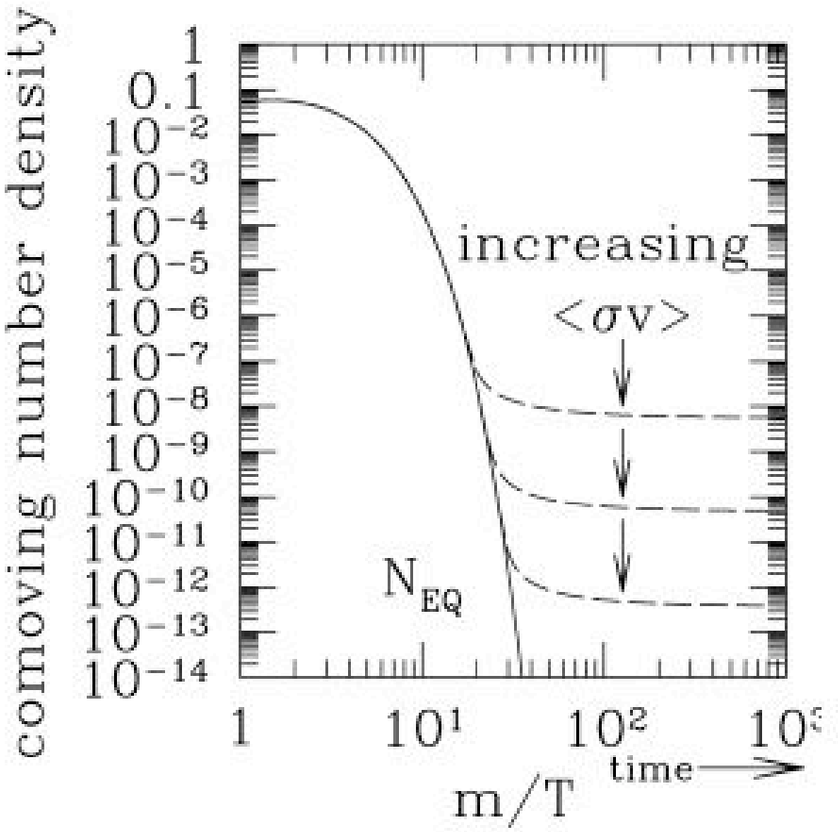
Only NP beyond SM discovered so far!

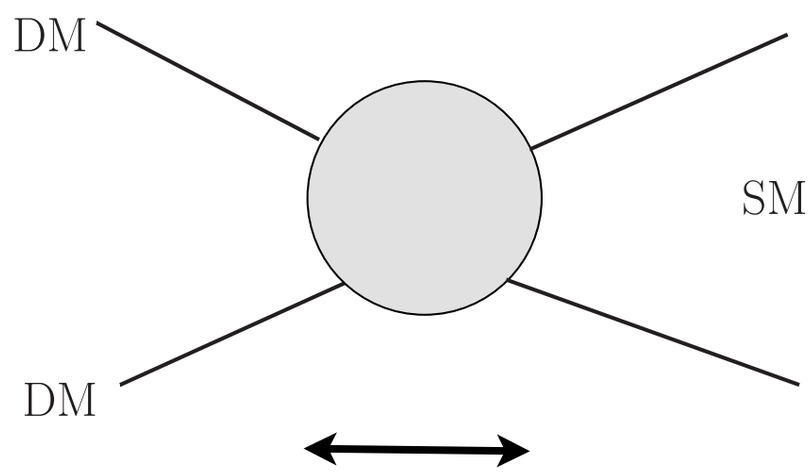


Dark matter candidate?

- We know very little. Vast range of possibilities
  - Can be 10^{-31} GeV to 10^{48} GeV.
- WIMPs
  - A compelling story.
  - Most relevant for the collider searches.
- Others: axion, ...
  - Possible. But not relevant for collider searches.

WIMP miracle

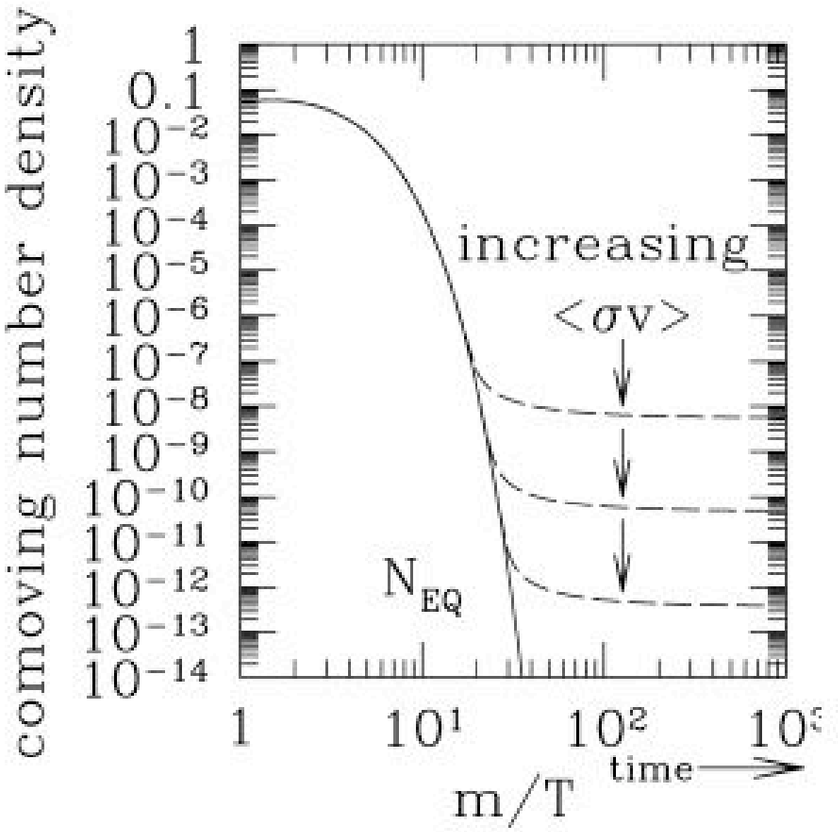


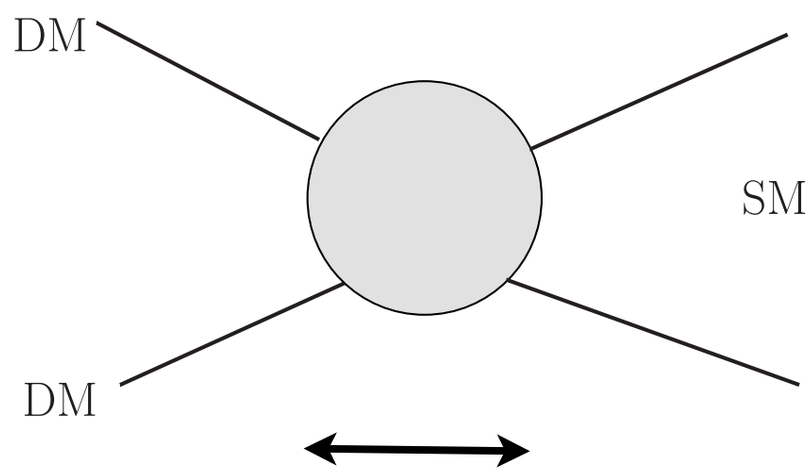


$$\langle \sigma v \rangle \sim \frac{g_{\rm D}^4}{m_{\rm DM}^2}$$

- If $g_D \sim 0.1$ $M_D \sim$ 10s GeV - TeV
  - We get the right relic abundance of dark matter.
- Major hint for weak(±) scale new physics!

WIMP miracle





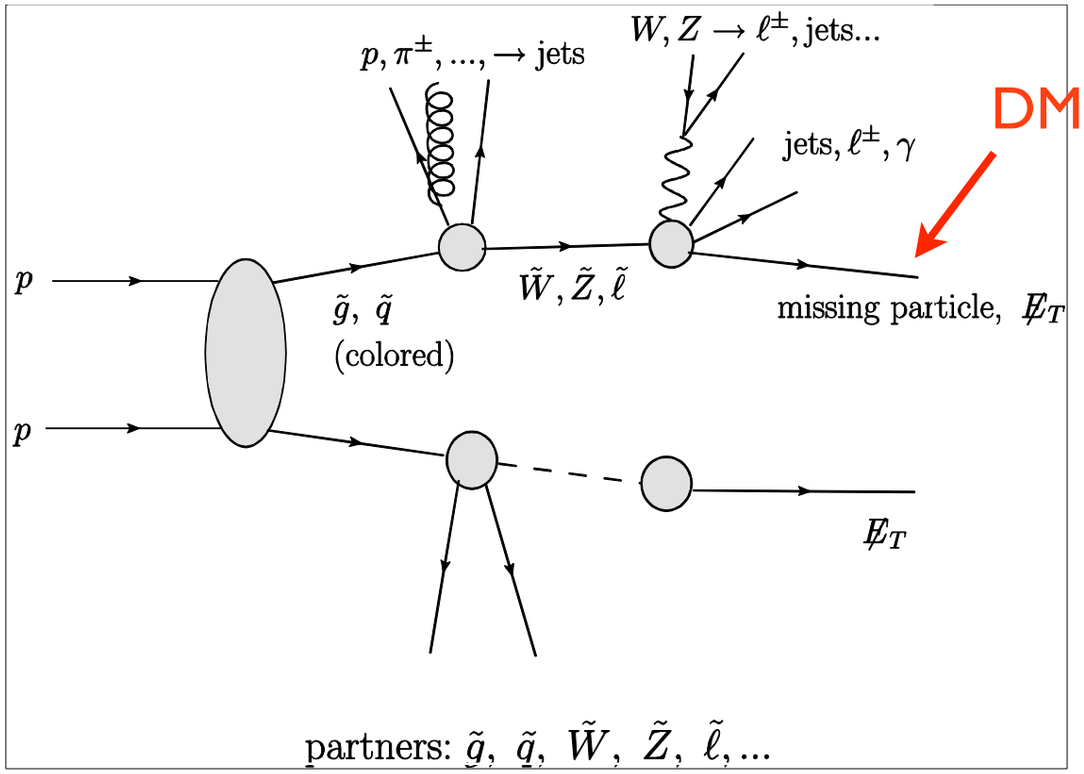
$$\langle \sigma v \rangle \sim \frac{g_{\rm D}^4}{m_{\rm DM}^2}$$

- More precisely, to get the correct relic abundance

$$M_{\rm WIMP} \leq 1.8 \text{ TeV} \left(\frac{g^2}{0.3} \right)$$

- Much of the parameter space out of reach for the LHC.

"standard" story.



SUSY, UED, etc.

- WIMP is part of a complete model at weak scale.
- It's produced as part of the NP signal, shows up as missing energy.
  - Dominated by colored NP particle production: eg. gluino.
- The reach is correlated with the rest of the particle spectrum.

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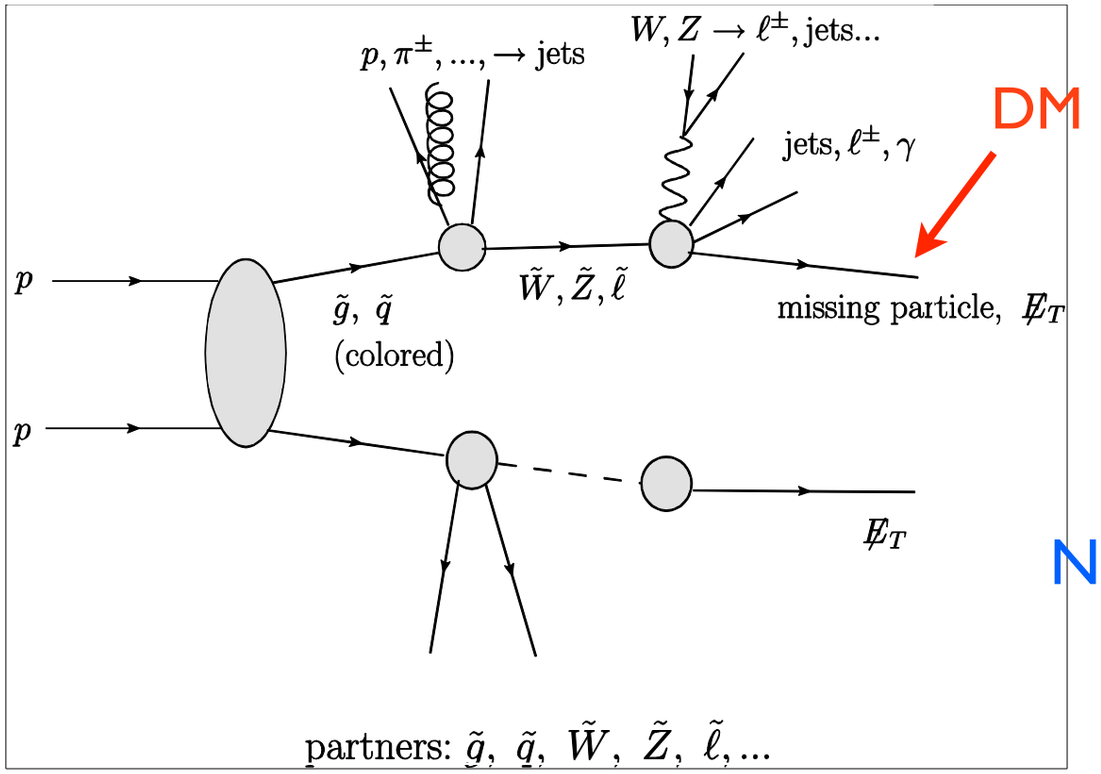
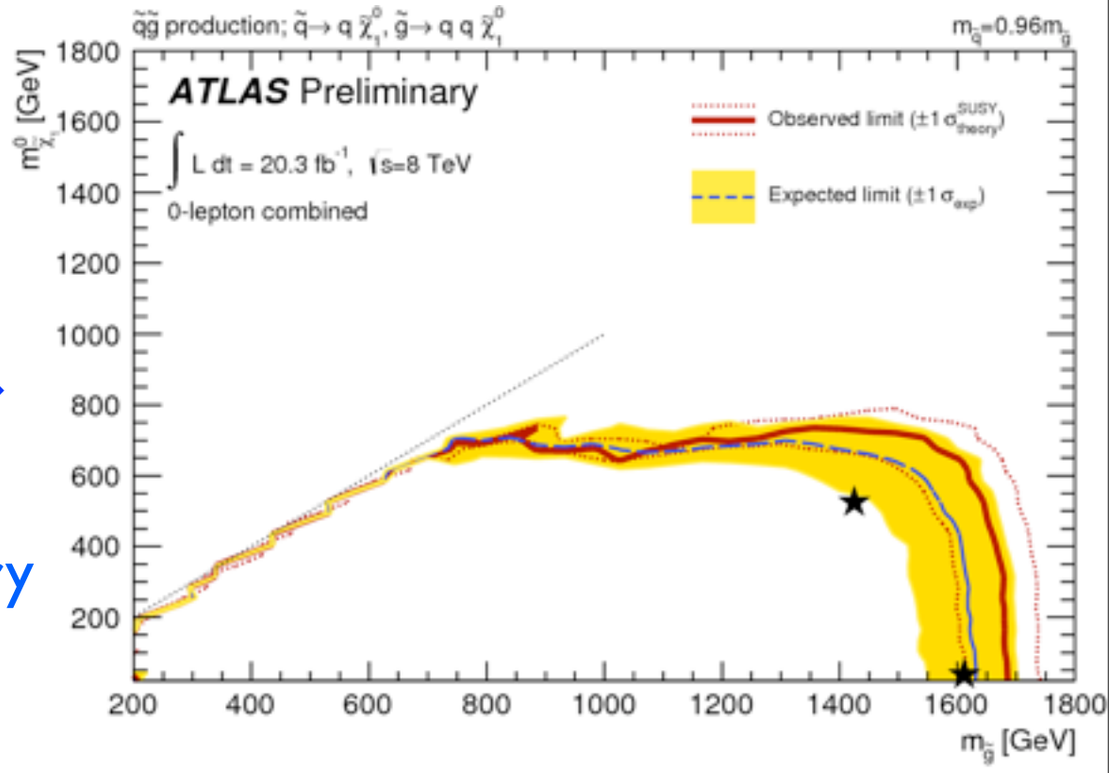


SUSY, UED, etc.

No discovery yet



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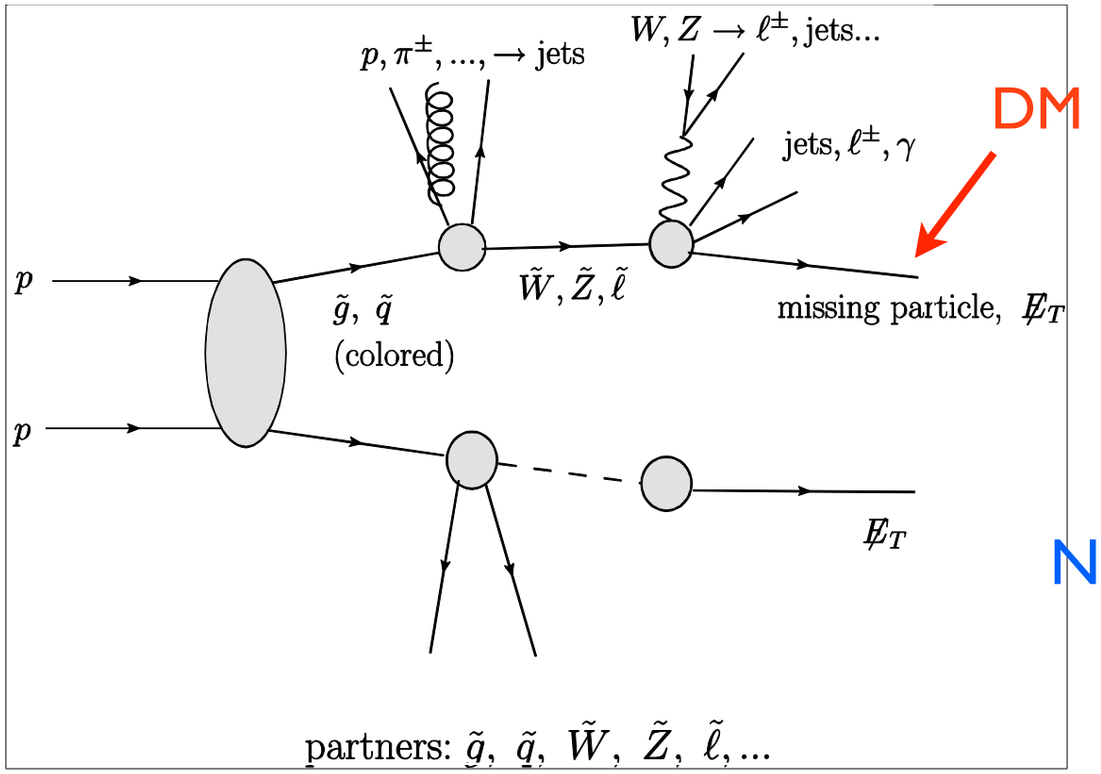

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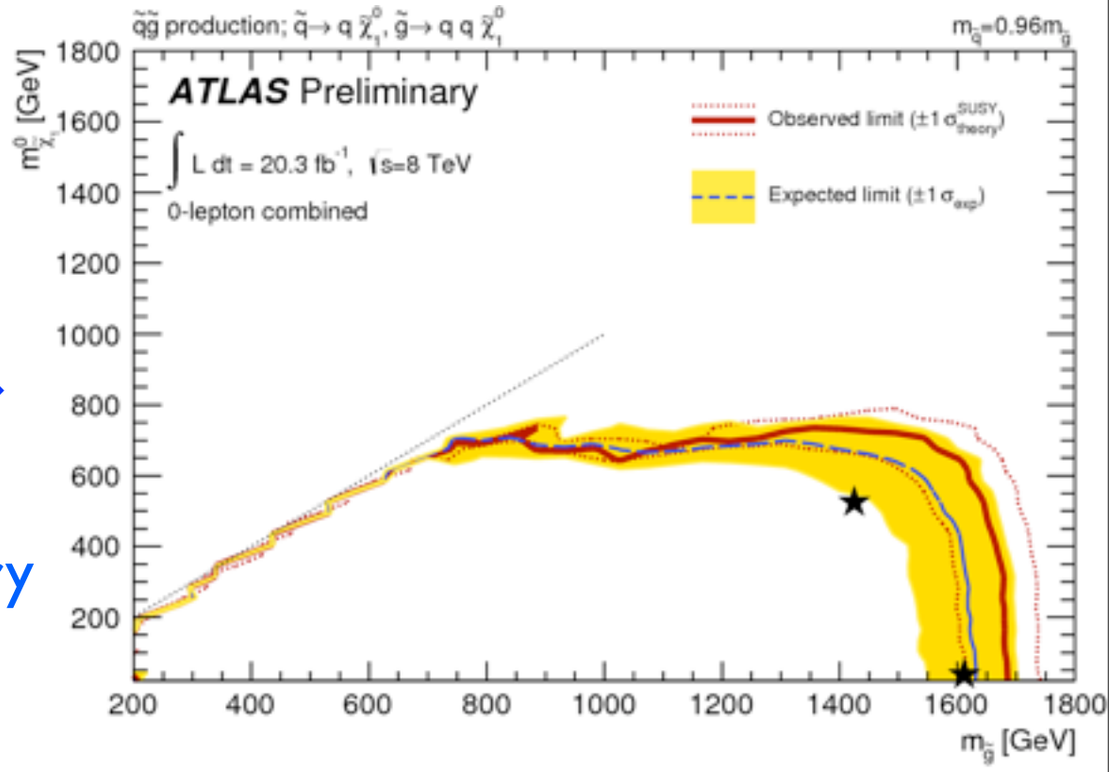
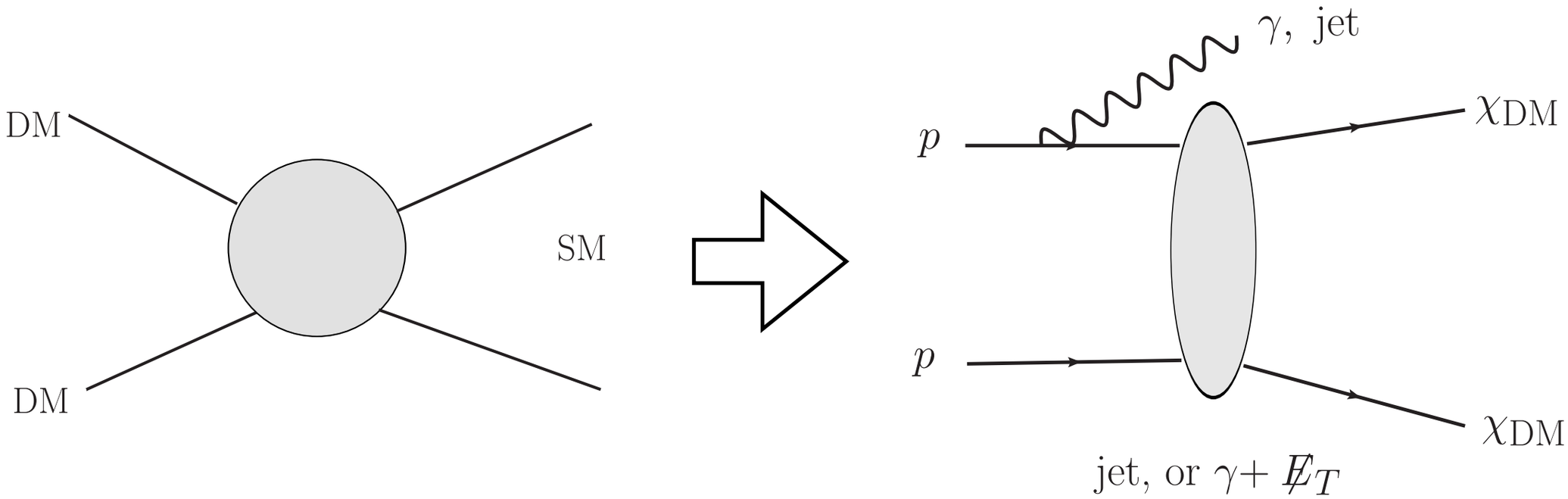


Of course, still plausible at the LHC, will keep looking.
Higher energy ⇒ higher reach

More basic channel

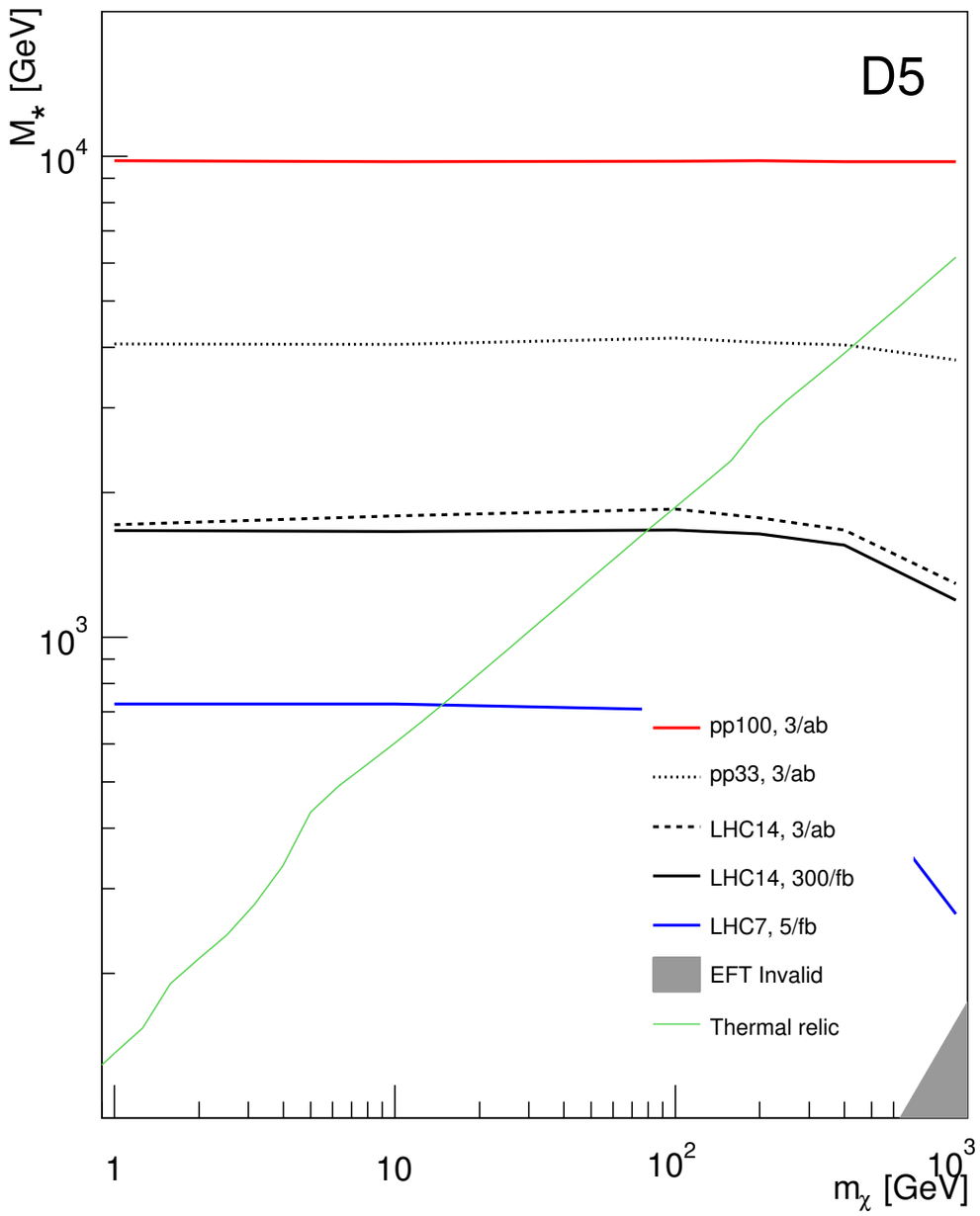
- pair production + additional radiation.

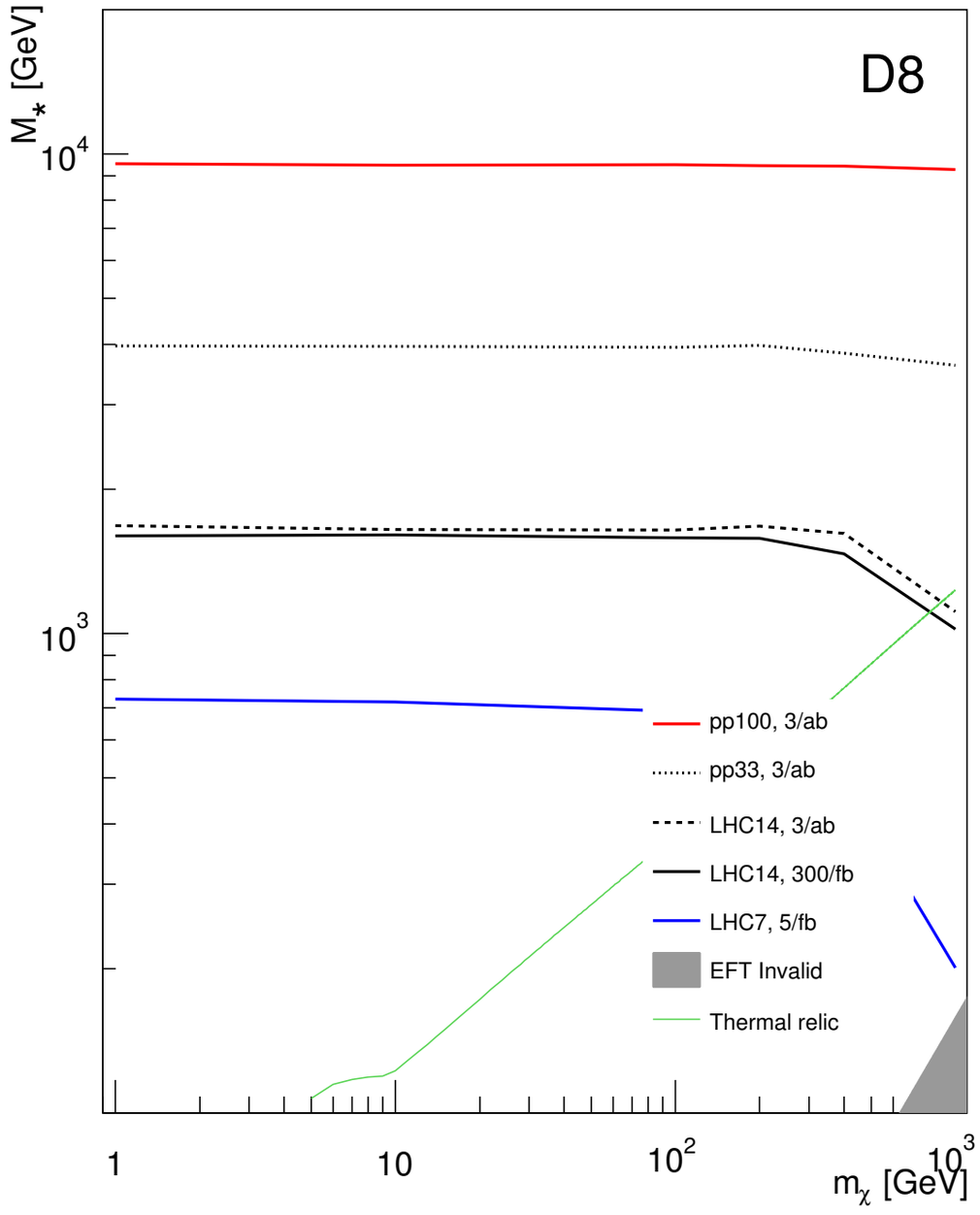


- Mono-jet, mono-photon, mono-...

- Have become "Standard" LHC searches.

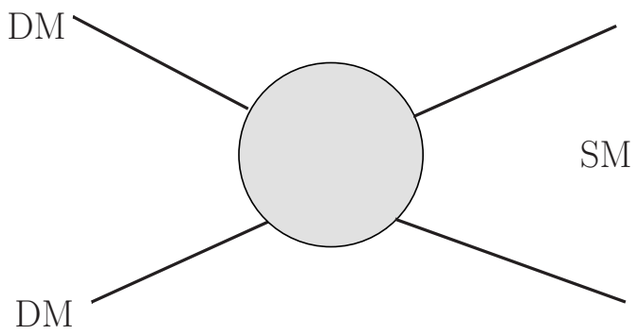
At future colliders





Snowmass, 2013

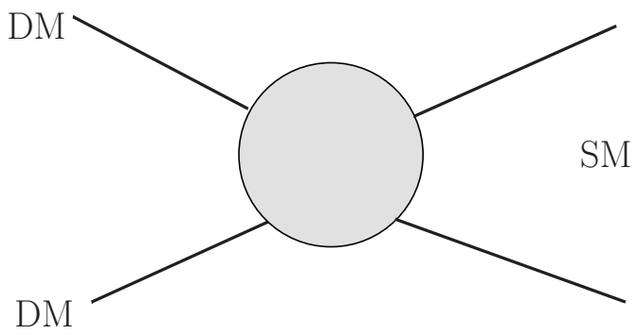
EFT effective?



=

- Valid as field theory?
  - Already questionable in run 1, will be quite problematic at for run 2.
  - Much worse at 100 TeV. Overestimation of the reach.
- At the same time, missing other physics opportunities, such as additional states to look for.

EFT effective?



$$= \frac{1}{\Lambda^d} \chi\chi J_{\mathrm{SM}}$$

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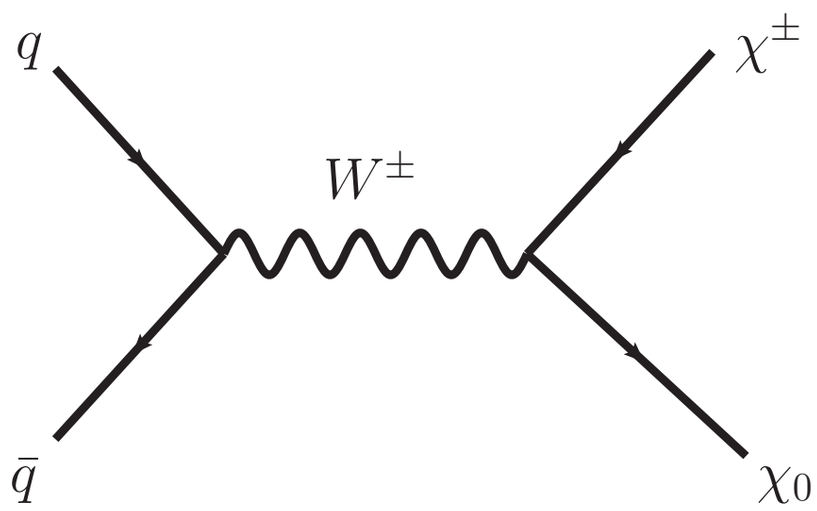
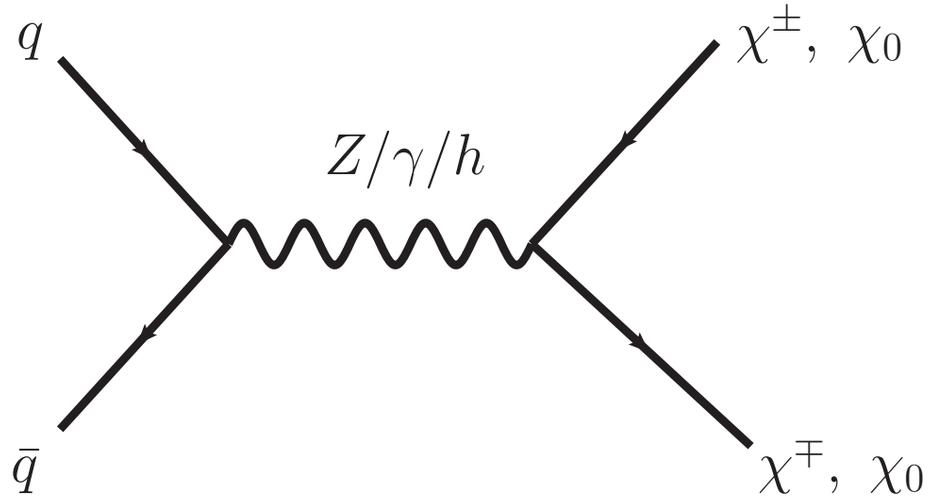
Two simple ways of going beyond

- Dark matter in a weak multiplet.
  - Mediators = W/Z/h
- Singlet dark matter + new mediator

DM part of a weak multiplet



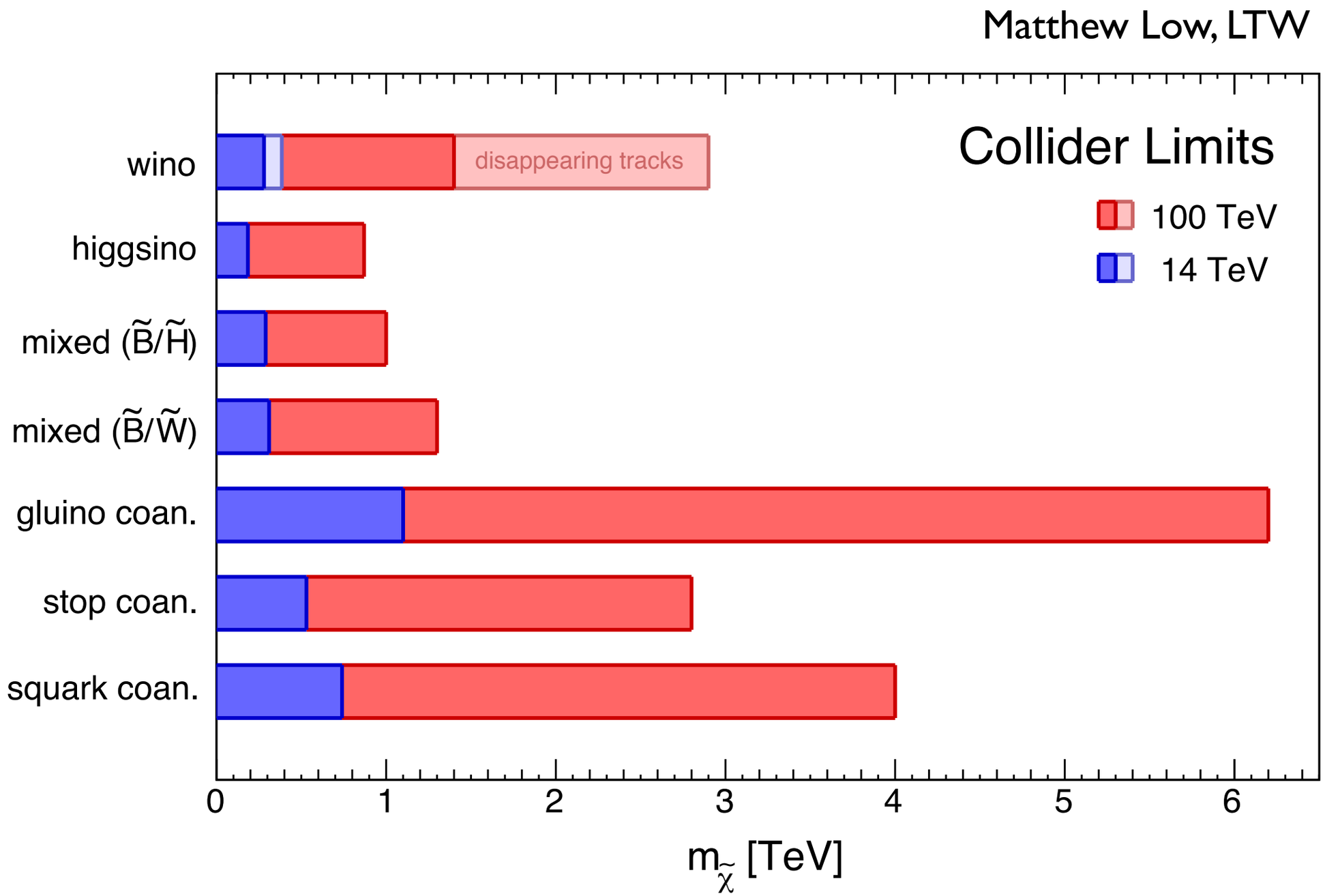


- Mediated by W/Z/h.

- Additional charged states.

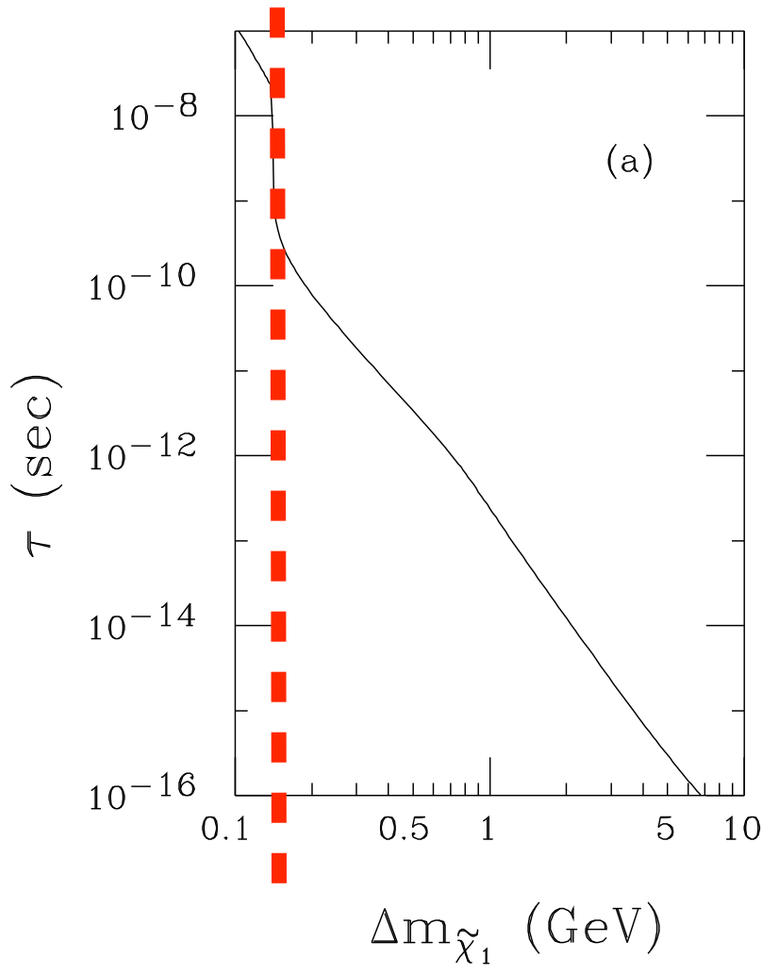
SUSY as an example

- Not just because we love SUSY.
- SUSY LSP ⇒ a set of good examples of more generic WIMP candidates.
  - Bino ⇔ singlet fermion dark matter
  - Higgsino ⇔ Doublet. Heavy exotic lepton.
  - Wino ⇔ EW Triplet DM
  - Can have co-annihilation regions



- Significant step beyond the LHC.

Disappearing track



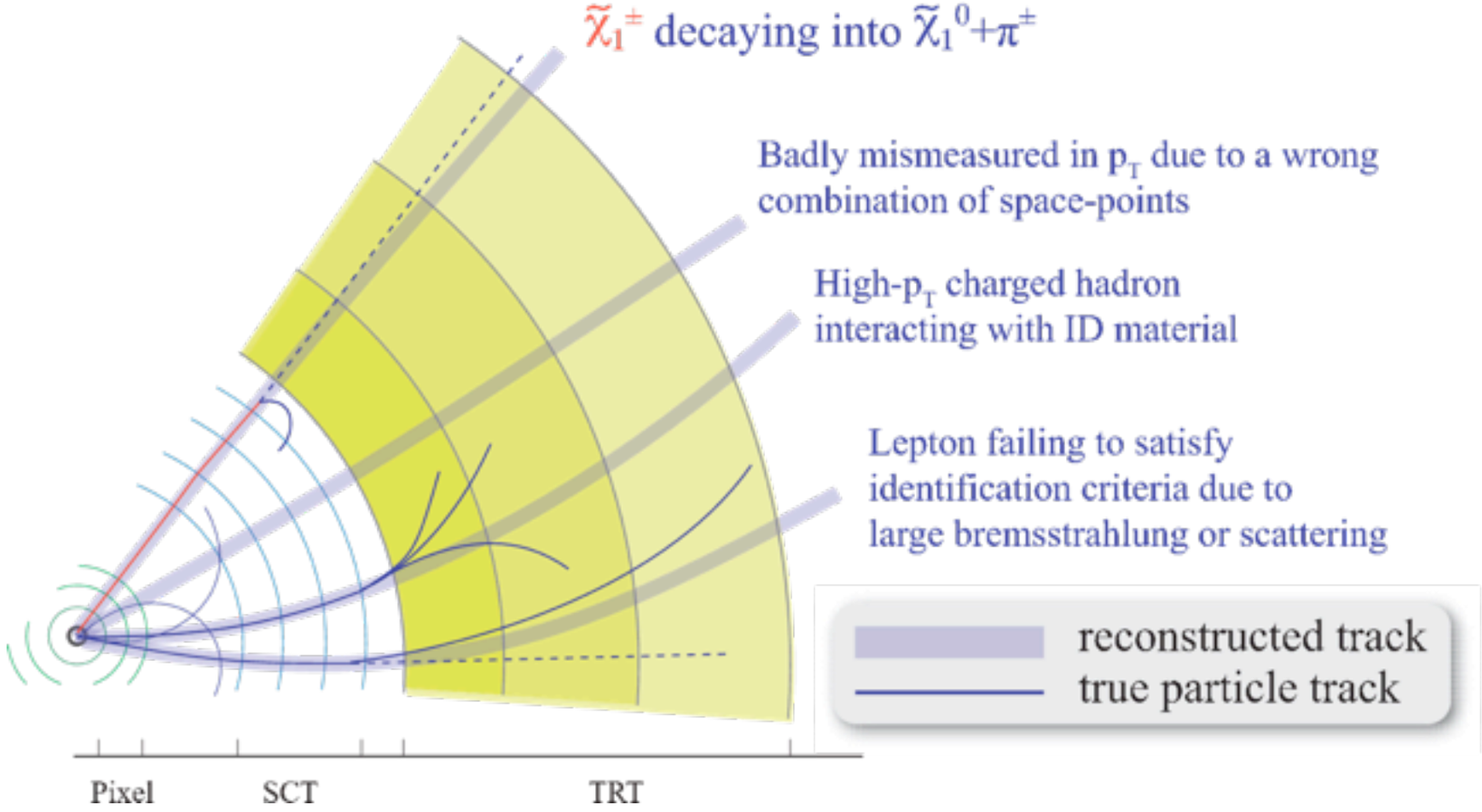
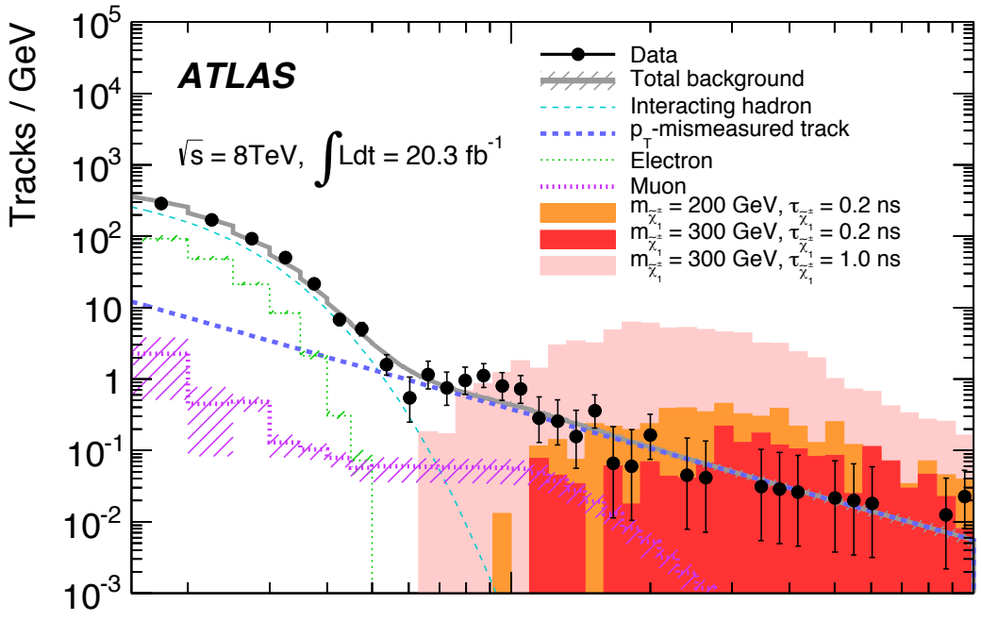


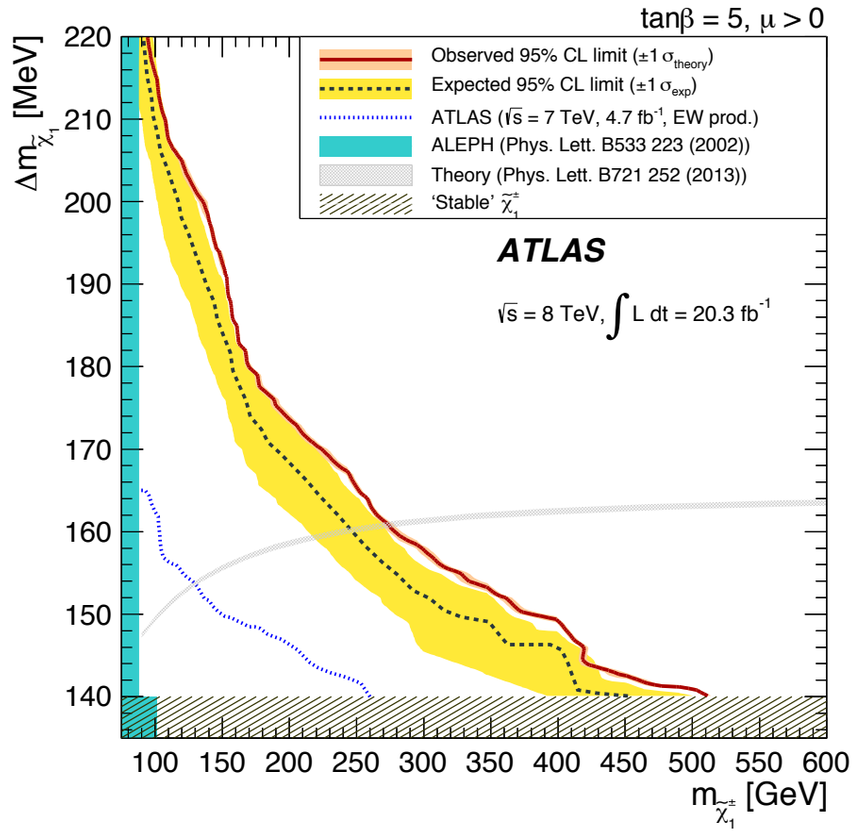
Figure from ATLAS disappearing track search twiki

- Main decay mode $\chi^{\pm} \rightarrow \pi^{\pm} + \chi^{0}$
- Charge track ≈ 10(s) cm

ATLAS search

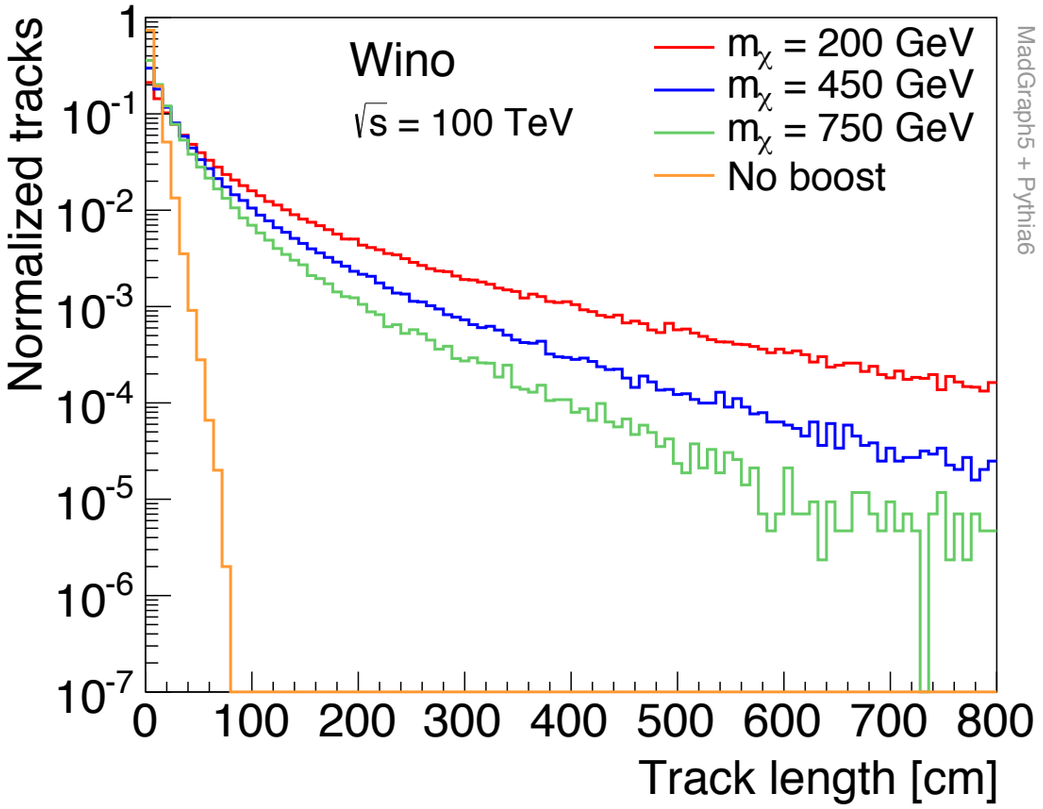
ATLAS, 1310.3675

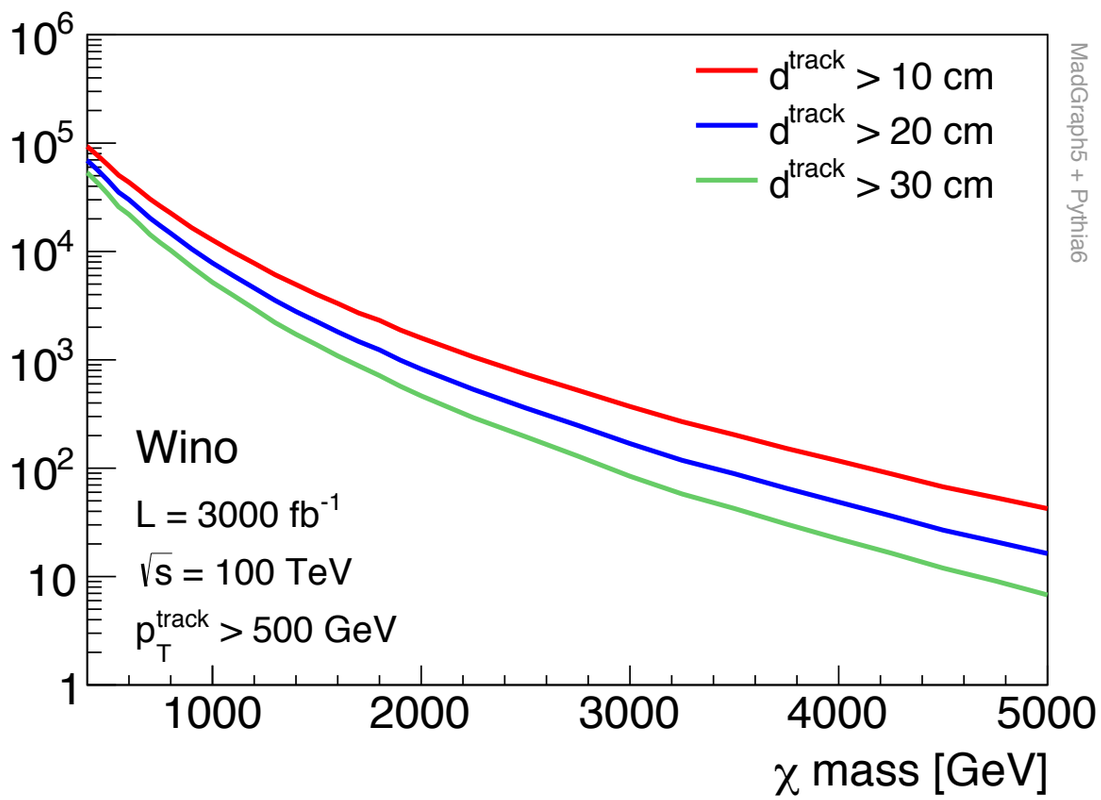




- Essentially free of physics background.
- Dominated by p_T mis-measured tracks.
- Very promising reach, much better than mono-jet

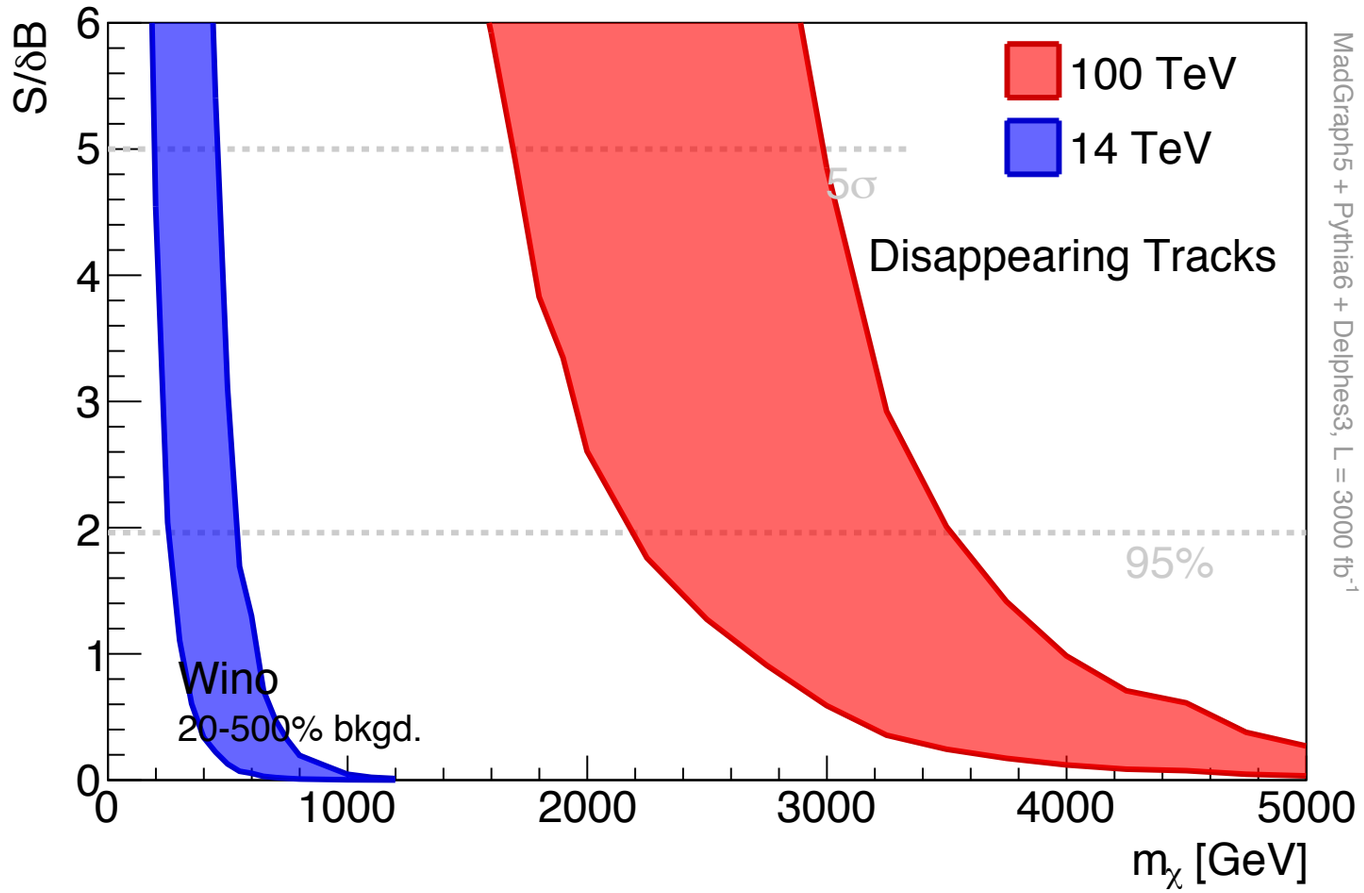
Rates (with long tracks)





- Disappearing track, stub, kink...
- Could also be long lived

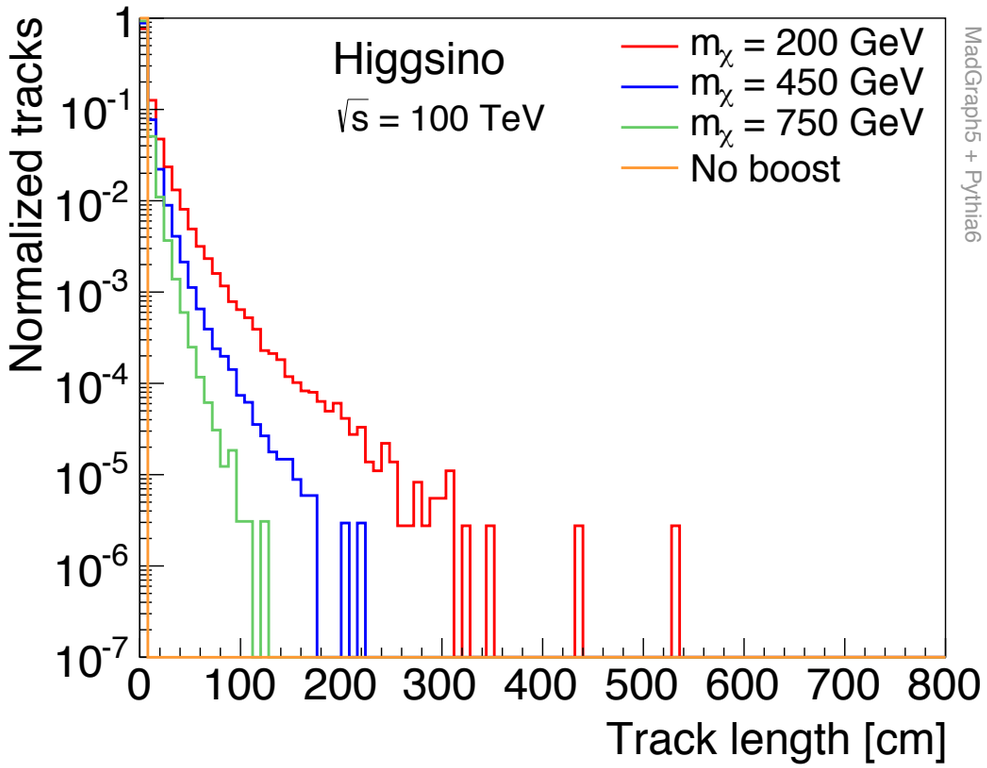
(Rough) Extrapolation from ATLAS search

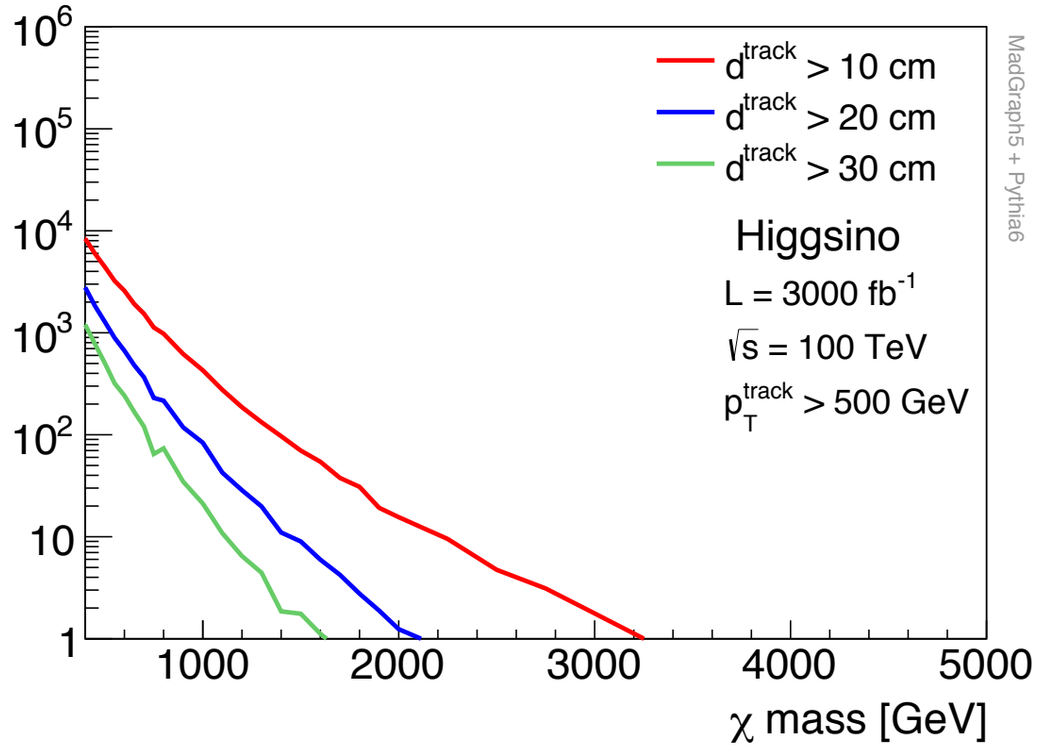


- Scale the ATLAS background rates according to hard jet + MET rates.

- Band: varying background estimate by 5 either way.

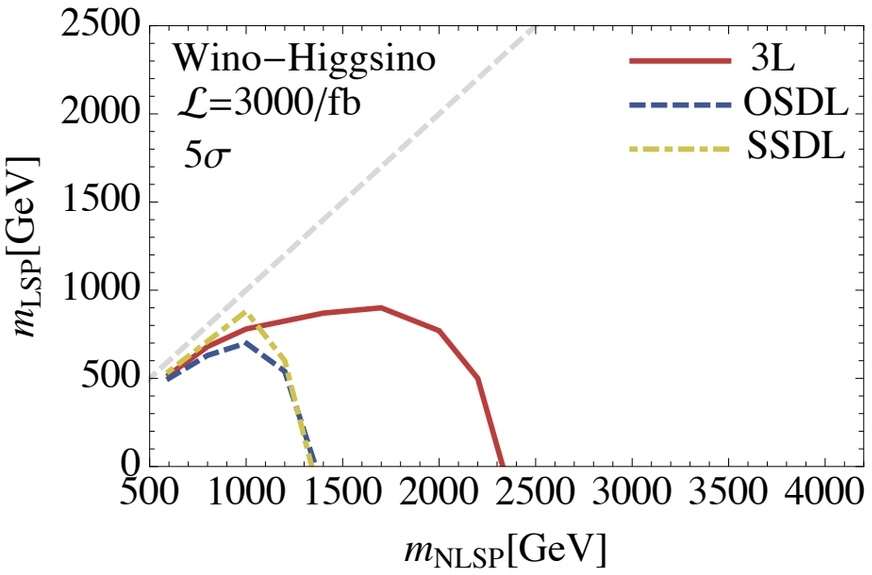
Do something about Higgsino?

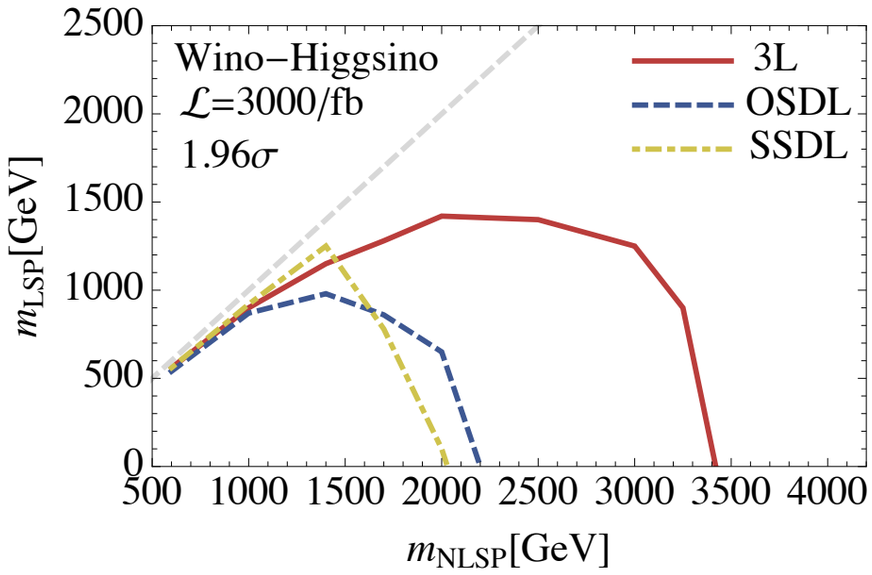


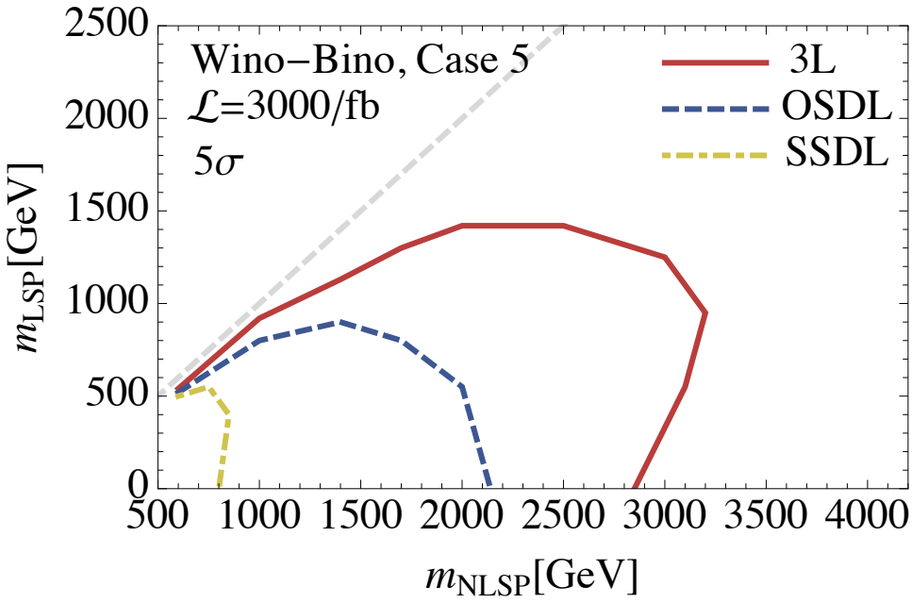


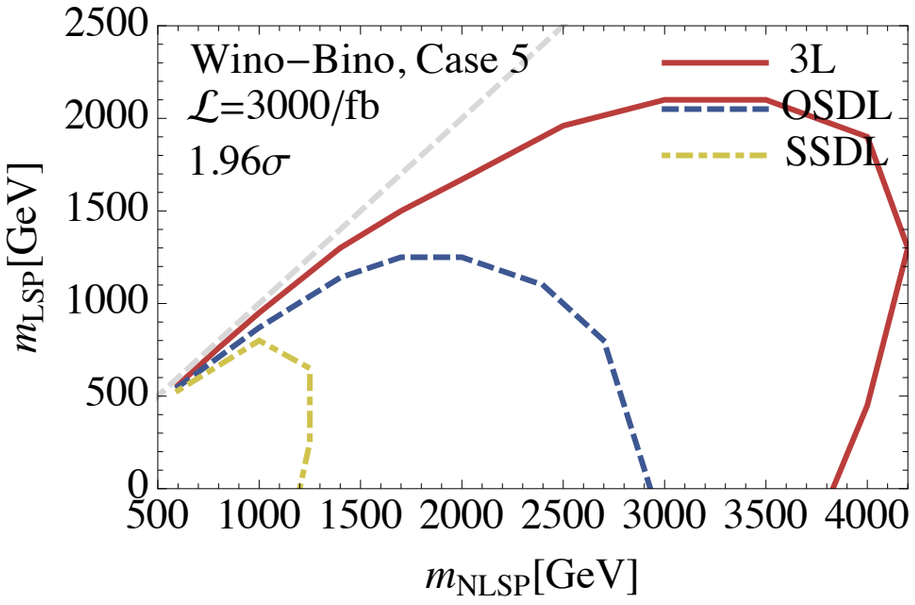
- Depends on detector design
  - How long the track needs to be?
  - Background discrimination?
- Can change mass splitting in extended models.

Casascade, multilepton searches.



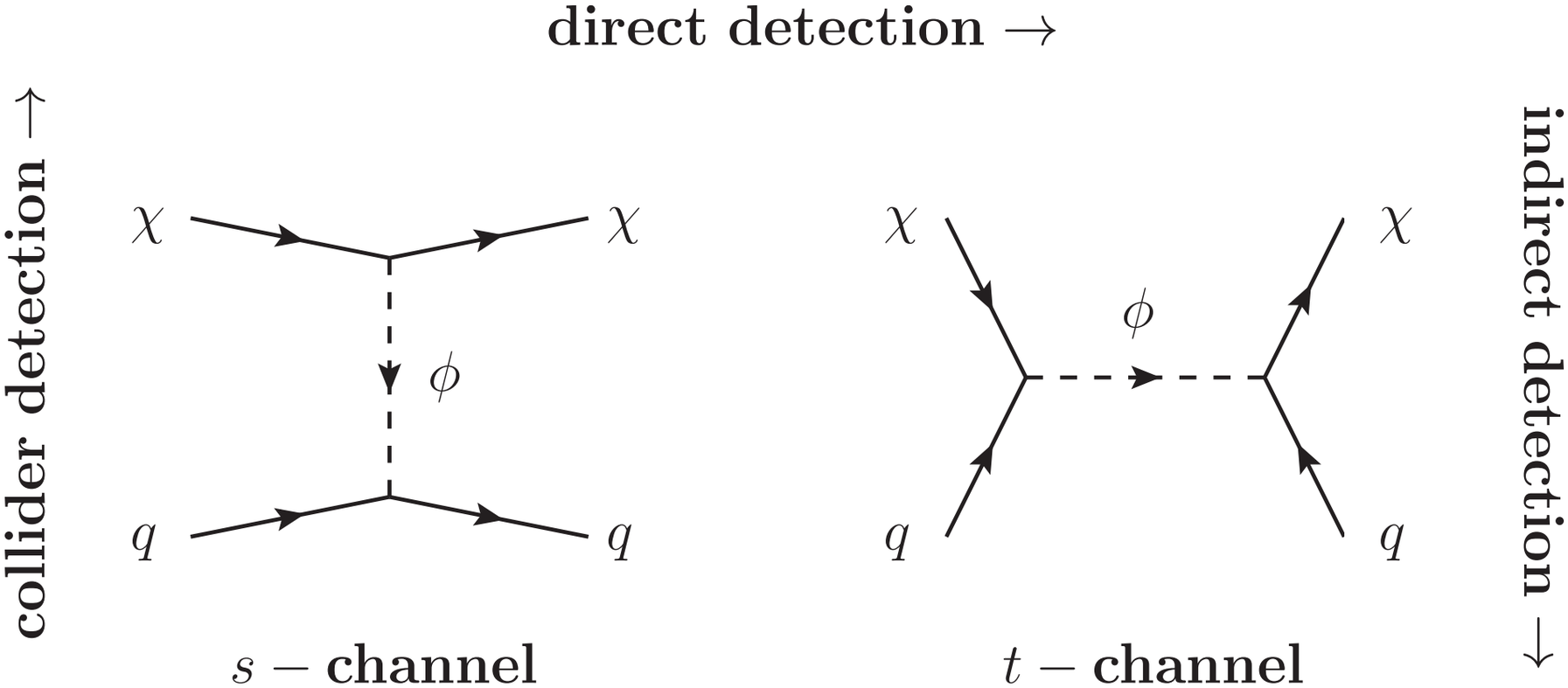






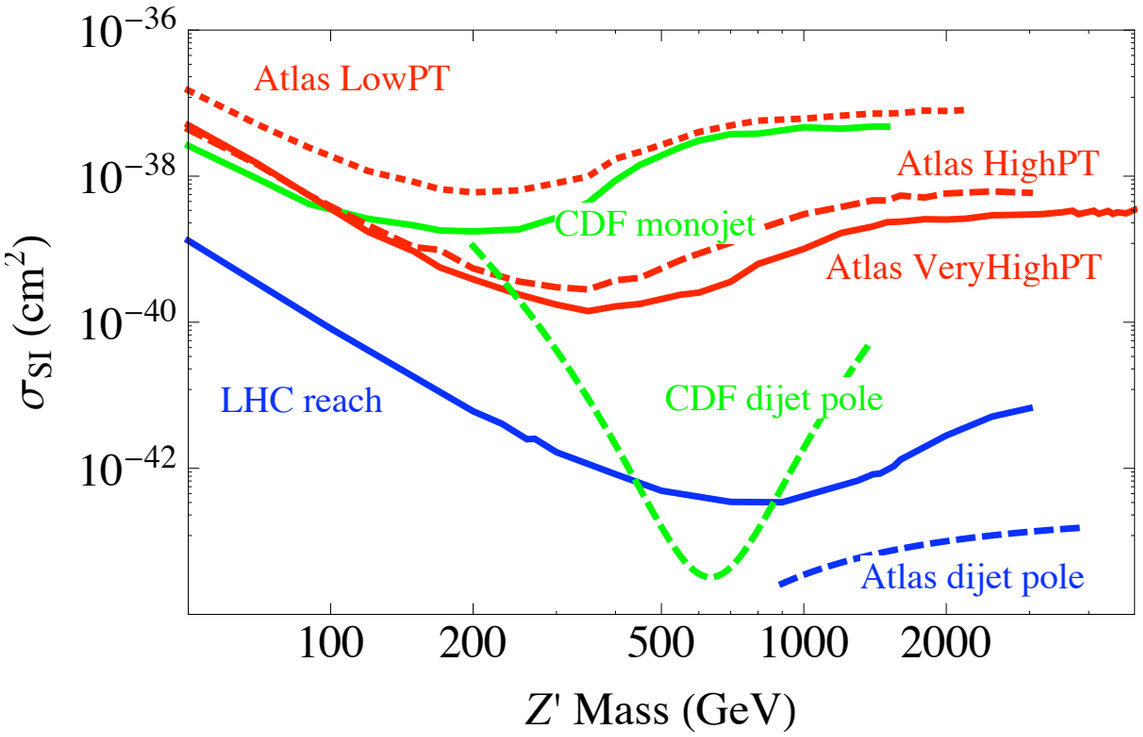
Gori, Jung, Wells, LTW, to appear

2. Simplified mediator models

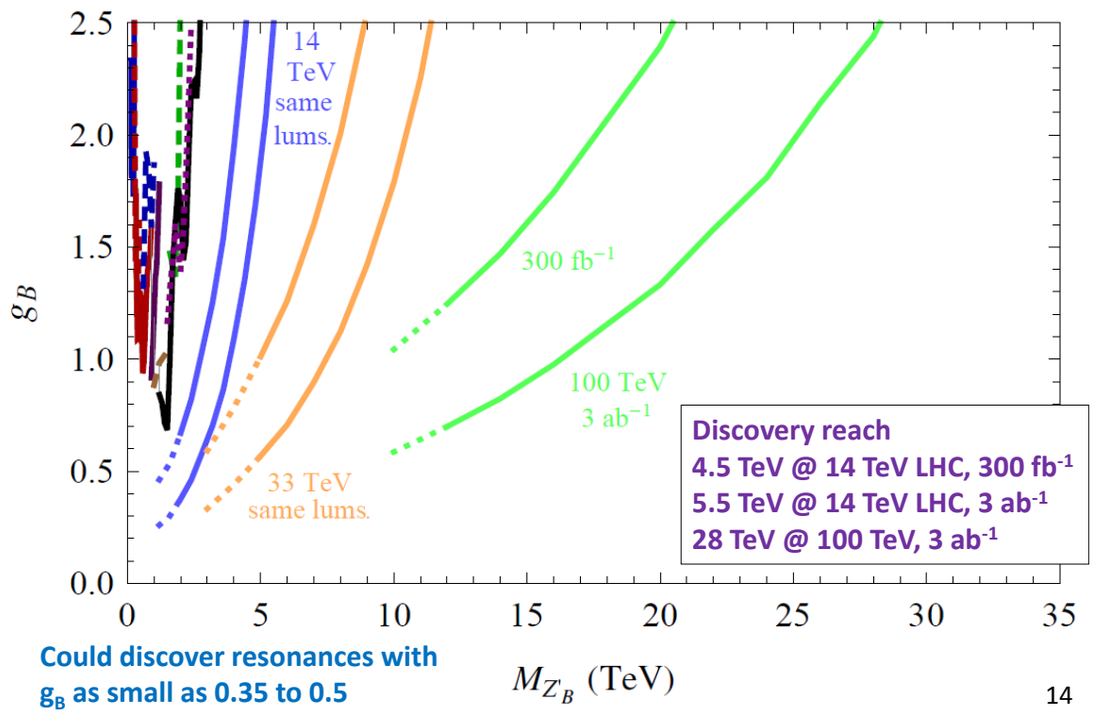


- can be scalar or Z’
- squark like

Possible to discover the mediator first!



An, Ji, LTW, 1202.2894 Assume $g_{Z'} = g_D$



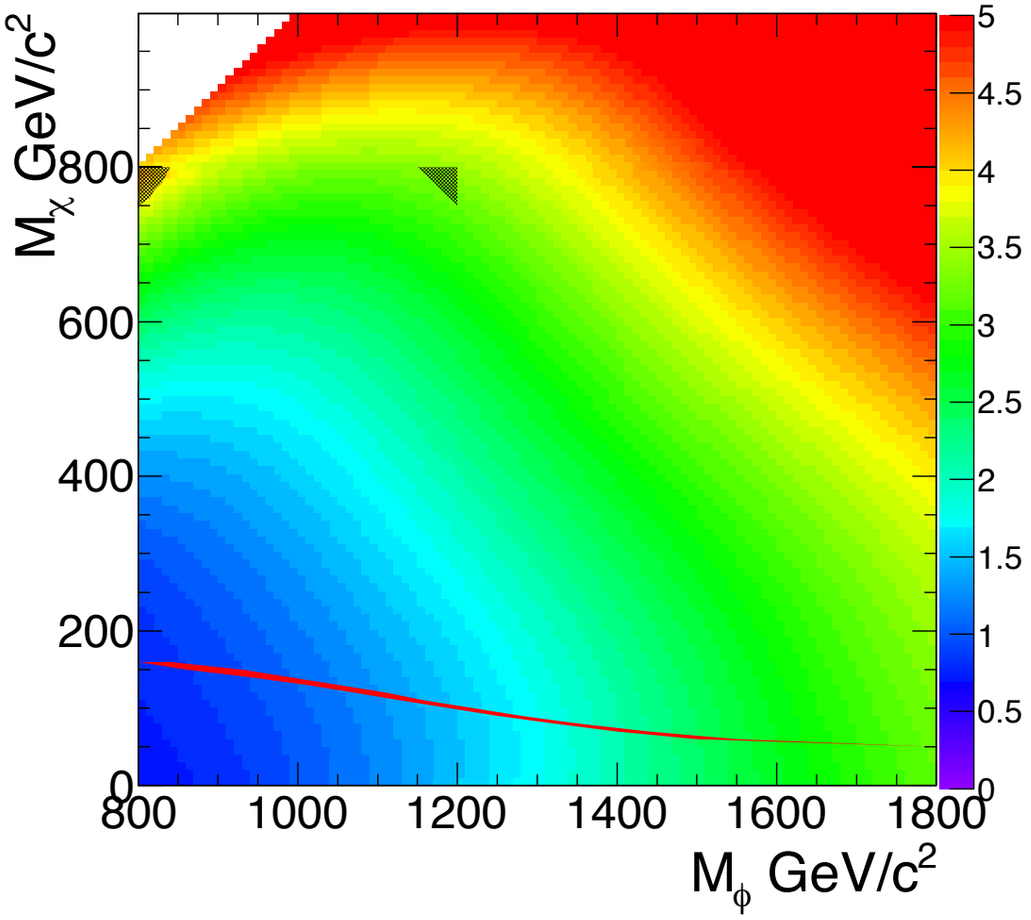
Could discover resonances with g_B as small as 0.35 to 0.5

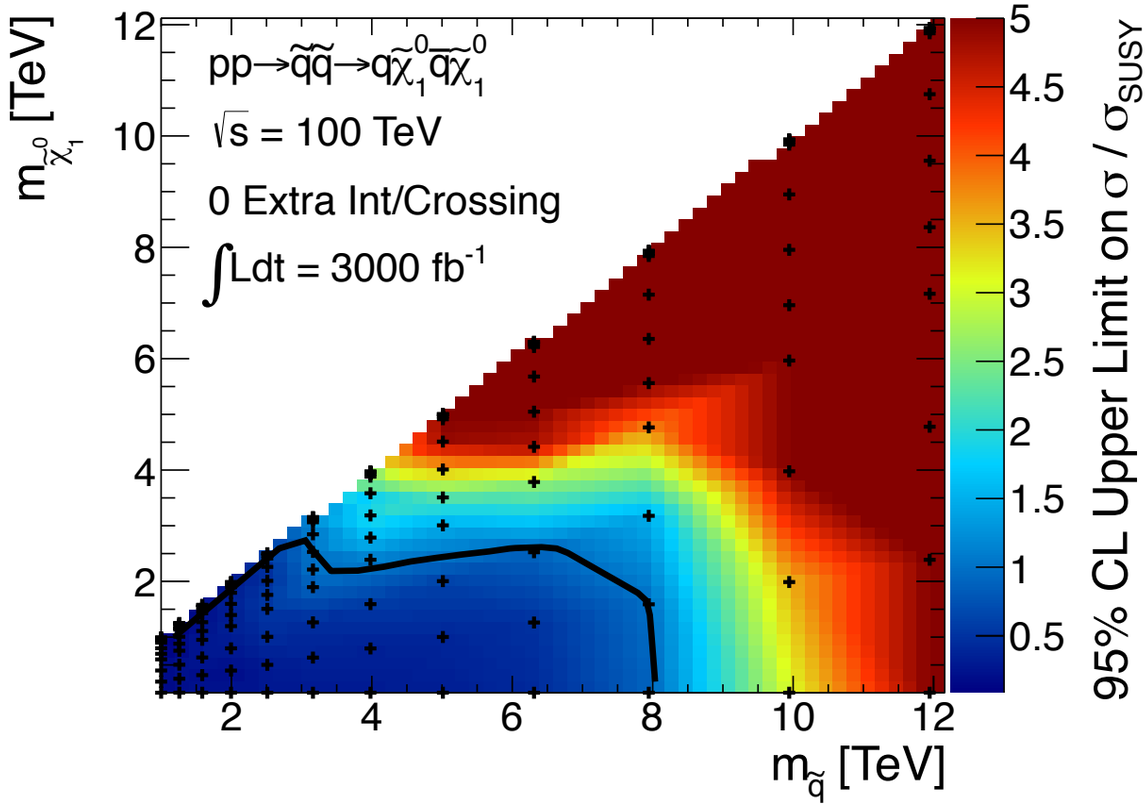
Felix Yu, 2013

Reaches

Monojet: CMS-PAS-EXO-12-048
squark: CMS-PAS-EXO-13-012

Dirac Contours, limits on coupling λ_q





In general, the processes involving mediator direct production give strongest limit.

Stronger limit come from squark search (gray) or CMS-style monojet search.

Haipeng An, Hao Zhang, LTW, 1308.0592

Conclusions

LHC	VLHC 100 TeV	Lepton collider
M_{DM} ~10^2s GeV	M_{DM} ~TeV	M_{DM} ~ 0.5 E_{cm} Spin, coupling Is it WIMP?

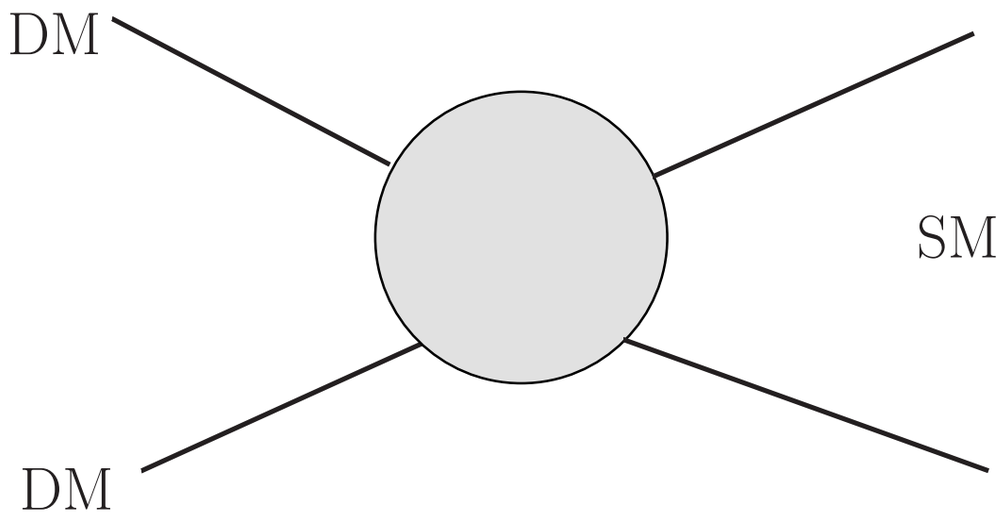
- Could also link to a possible dark sector.

Conclusion

- The search for WIMP dark matter is largely out of the reach for the LHC.
  - LHC 14: reach to about a couple hundred GeV.
- 100 TeV pp Collider signficantly enhance the reach, a fact of 5-7 enhancement.
- More detailed studies necessary. At the same time, it is clear that this should be one of the main motivations for going to a 100 TeV pp collider.

extras

Effective operator approach



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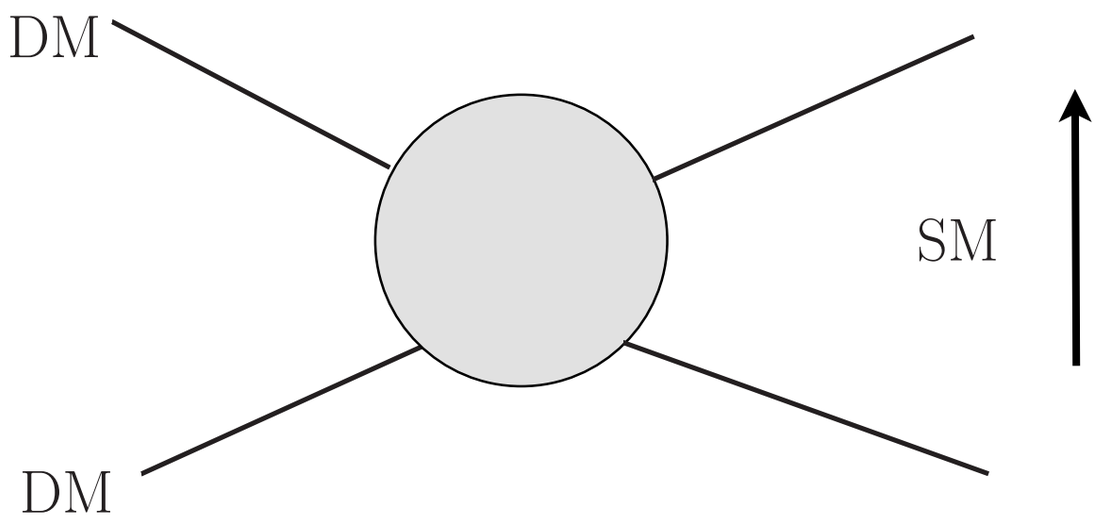
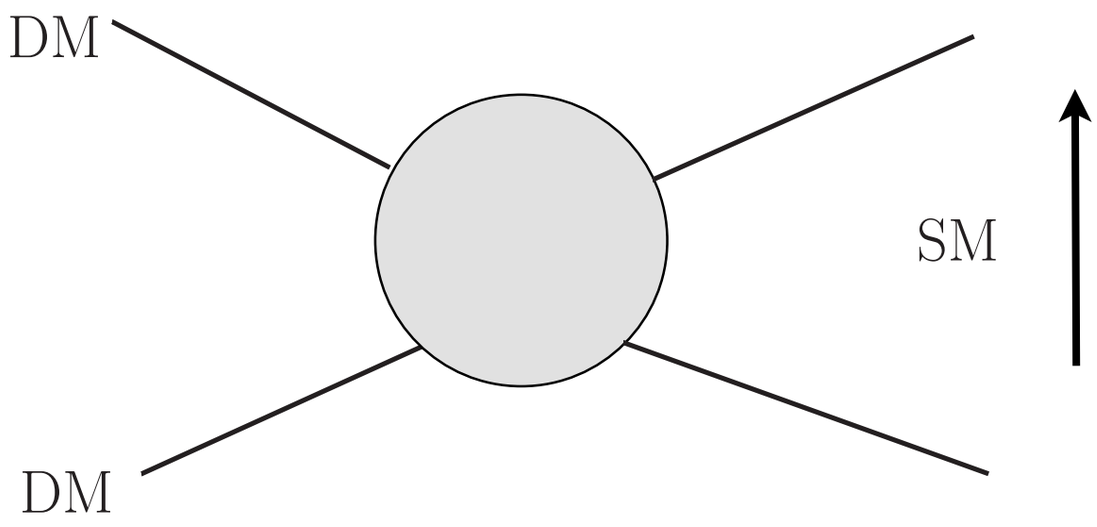


momentum exchange
q~100 MeV << m_Φ
effectively,

$$\frac{1}{\Lambda^d}\chi\chi J_{\rm SM}$$

Effective operator approach



momentum exchange
q~100 MeV << m_Φ
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$$\frac{1}{\Lambda^d}\chi\chi J_{\rm SM}$$

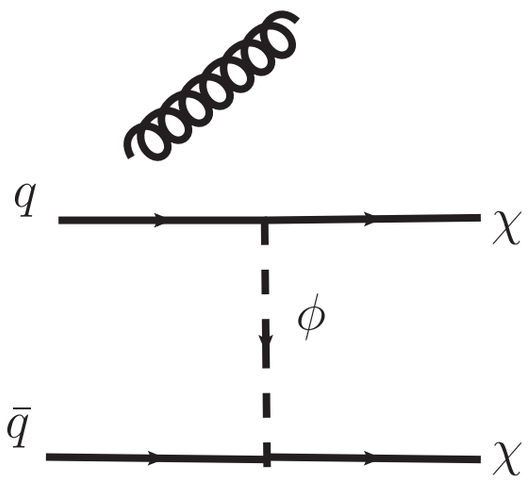
Use colliders to constrain and probe
the same operator

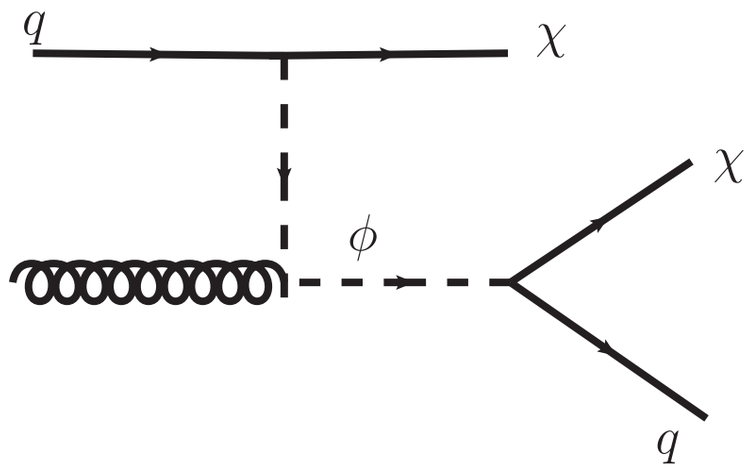
$$\frac{1}{\Lambda^d}\chi\chi J_{\rm SM}$$

Beltran, Hooper, Kolb, Krusberg, Tait, 1002.4137
Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu, 1005.1286
Bai, Fox, Harnik, 1005.3797 .....

Collider searches

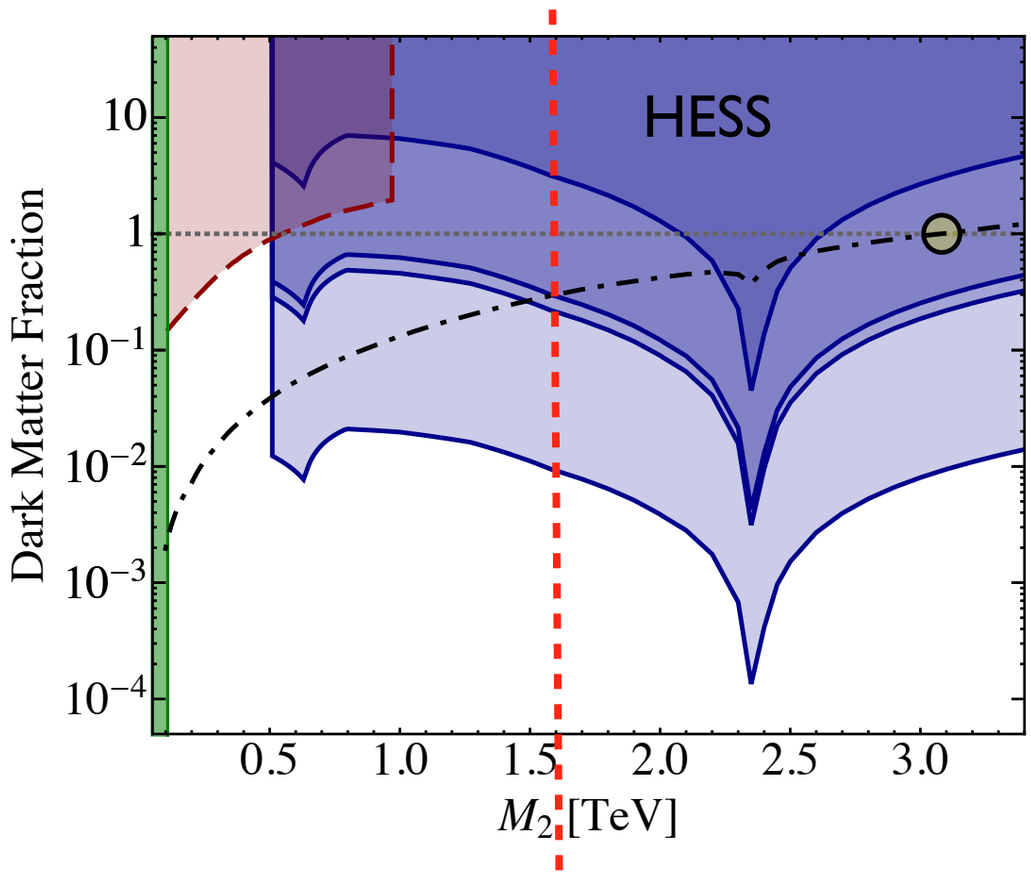
$$\mathcal{L}_\chi = \lambda_q \bar{\chi} \phi^* q + h.c.$$

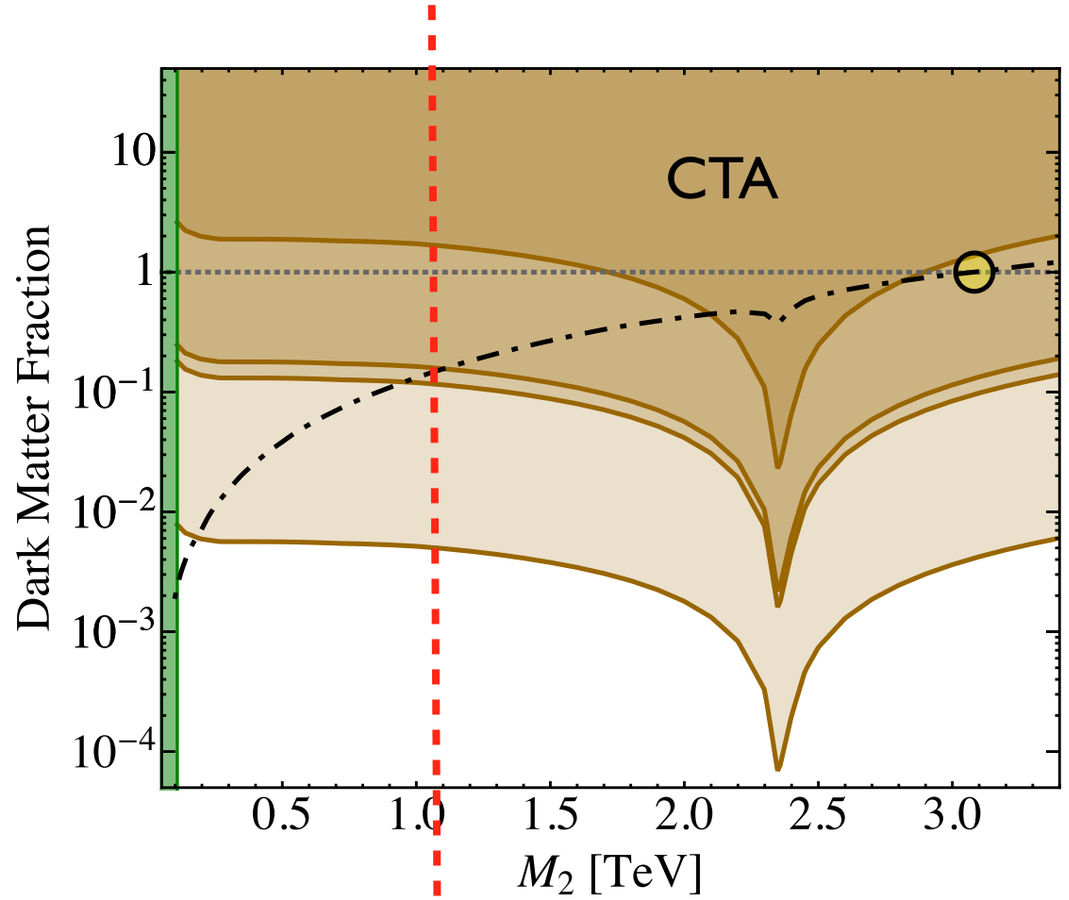




- 2 kinds of contributions for monojet.
- $pp \to \chi\phi$ gives harder (mono)jet!

Wino, interplay with indirect detection

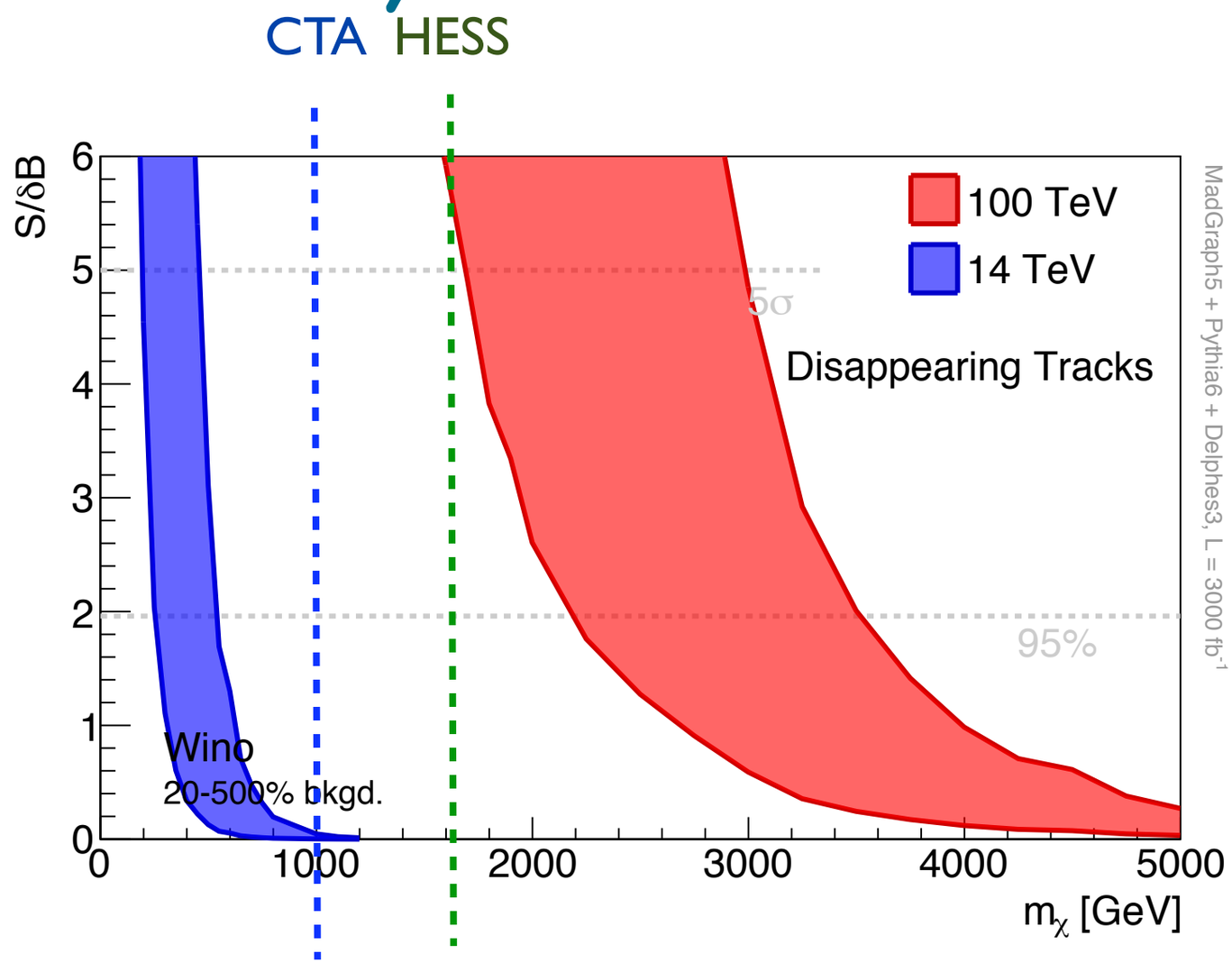




Cohen, Lisanti, Pierce, Slatyer, 1307.4082

See also Fan, Reece, 1307.4400

Wino summary



- Completely cover the wino parameter space.